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ESTIMATION OF WAVE PROPAGATION VELOCITY ON A CHANNEL WITH SMOOTH AND ROUGH BED

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ABSTRACT

Natural hazards such as tsunamis, impulse waves and dam-break waves are rare, but extremely destructive. In recent times, more importance was given to structures that could withstand such events, however, uncertainties still exist in the estimation of wave velocities. This project focuses on the estimation of wave front celerity in a laboratory environment for both smooth and rough beds and the results are successfully compared to previous studies and design codes. Based on the experimental data an expression for the wave celerity is presented and discussed. The influence of bed roughness on the propagation velocity is also investigated and a dependence on the bed friction is observed, pointing out the need for further studies.

Keywords: Tsunami; impulse wave; dam-break wave; wave front celerity; bed roughness.

1 INTRODUCTION

In the past, the impacts of hydrodynamic waves on structures were considered extremely rare events and wave induced forces were typically neglected in the design process. In nature, the sudden release of a large amount of water can be found in impulse waves and tsunamis. Dam-break waves have similar behaviours and their solid theoretical background is widely used to describe the behaviour of hydrodynamic waves. Some recent catastrophic events that took place in the Indian Ocean (2004), in Chile (2010) and in Japan (2011, Figure 1), with large damages and casualties have shown that measures had to be taken to guarantee human safety and reduce reconstruction costs in coastal areas.

Figure 1. Tsunami propagating inland during the Japan 2011 event (Keystone, 2011).

Nowadays, the newly released design codes put emphasis on the importance of hydrodynamic forces in the design process and the role of engineers and researchers is becoming fundamental to alleviate the consequences of such events. In most design codes all over the world, hydrodynamic forces are computed using the wave front propagation celerity, however, its estimation is covered by high incertitude. In the past, many studies were carried out investigating the magnitude of wave celerity, including both experimental (Matsutomi and Okamoto, 2010; Shafiei et al., 2016; Wüthrich et al., 2017) and field surveys (Rossetto et al., 2007; Fritz and Okal, 2008; Chock et al., 2012). Nevertheless, the consistent amount of formulae available in literature showed that disagreement still exists in the evaluation of the front celerity (Nistor et al., 2009). As the force proportional to the squared value of the velocity, these uncertainties are amplified in the computation, resulting into large differences in magnitude of the resulting forces. A more precise estimation of wave velocities is therefore necessary to improve the design process, taking into account the influence of bed roughness, whose values are assumed to play an important role.

2 EXPERIMENTAL SET-UP

For the present study, tsunami generation was achieved through the sudden release of a known volume of water from an upper basin into a lower tank and then into the channel. Similar wave generation techniques were previously used by Chanson et al. (2002), Lukkunaprasit et al. (2009), Meile et al. (2011), Rossetto et al. (2011) and Wüthrich et al. (2017). In the current facility, different released volumes resulted into waves with various equivalent impoundment depths, d_0 ranging between 0.40 m and 0.82 m if a classical dam-break waves is considered. This corresponded to waves with different hydrodynamic properties, mainly wave height and celerity. The waves propagated in a horizontal channel with a length of 15.5 m and a width of 1.5 m. The smooth surface was represented by painted wooden panels, whereas for the tests over rough bed, an artificial carpet was added; the latter had a thickness of 7 mm. The Darcy-Weissbach friction factors for both channels were deducted through free surface profiles leading to average values of $f \approx 0.02$ and $f \approx 0.04$ for the smooth and rough configurations respectively, corresponding to roughness values ε = 1.4 mm and ε = 2.4 mm. These values are consistent with the findings of Choufi et al. (2014) for similar materials. The facility used in the present study is shown in Figure 2 for both smooth and rough configurations. Both dry bed surges and wet bed bores were produced in the present study. The initial still water depth, h_0 was controlled through a sill located at the downstream end of the channel. The propagating surges and bores were investigated in terms of wave height, using 7 Ultrasonic distance Sensors (US) located at x = 2.00, 10.10, 12,10, 13.10, 13.35, 13.60 and 13.85 m from the channel inlet. These were sampled at a frequency of 12.5 Hz with a precision of ±0.5mm.

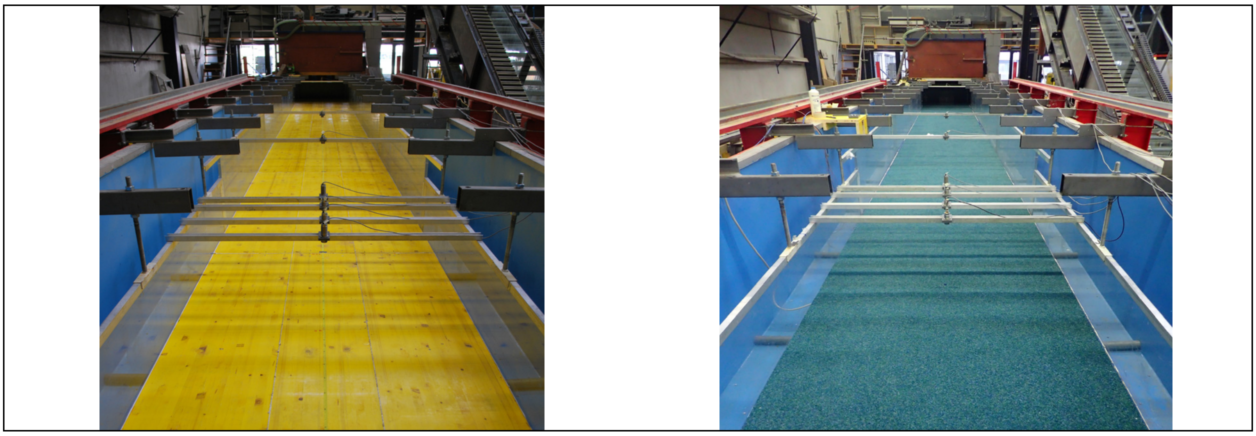

Figure 2. Figure of the experimental set-up: (left) smooth bed, (right) rough bed.

The tested waves reached heights of 0.30 m and front celerity of 3.5 m/s at model scale. If a 1:30 Froude scaling ratio is assumed, these values corresponded to typical configurations observed in coastal areas subject to tsunami hazard. The arrival of the wave was set when a water depth of 0.01 m was measured. Knowing the spatial repartitions Δx of the US sensors, an estimation of the wave propagation celerity was obtained through the ratio $\Delta x/\Delta t$.

3 METHODOLOGY

This project specifically focused on the estimation of wave front velocities in laboratory environment and results were compared to previous studies and existing design codes. The study is based on an experimental approach and the details of the 18 tests performed are presented in Table 1 along with some key parameters of the reproduced waves.

Table 1. Experimental program carried out for the present study.

Bed condition	Friction factor f	d_0 [m]	h_0 [m]	U [m/s]	h_{max} [m]	N. of repetitions
dry	0.02	0.82	-	3.57	0.20	3
dry	0.02	0.63	-	3.10	0.17	2
dry	0.02	0.40	-	2.35	0.13	2
dry	0.04	0.82	-	2.85	0.22	3
humid	0.04	0.82	0.001 m	2.89	0.23	1
wet	0.01	0.82	0.05 m	2.73	0.27	5
wet	0.04	0.82	0.05 m	2.74	0.28	2

4 VISUAL OBSERVATIONS

Both dry bed surges and wet bed bores were investigated in the present study. The difference in behaviour between surges and bores on smooth horizontal bed has been widely investigated in previous studies, including Ramsden (1996), Chanson (2004) and Wüthrich et al. (2016; 2017). Dry bed surges are characterized by a constant increase of water depth without aeration, whereas bores have a turbulent aerated front propagating along the channel. Surges are associated with higher velocities, whereas bores have greater wave heights. The same differences between surges and bores were also observed on the rough condition, as shown in Figure 3. Nevertheless, dry bed surges propagating on rough bed had higher wave heights and slower velocities compared to the smooth condition. Furthermore, the propagating front was more aerated. For wet bed bores, the difference in behaviour between the smooth and the rough condition was, visually, very small.

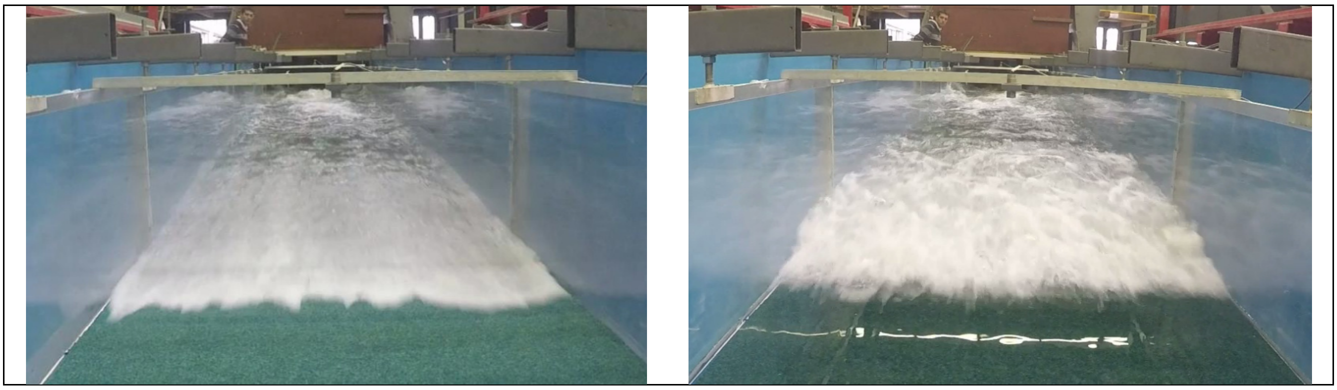

Figure 3. Dry bed surge (left, d_0 = 0.82m) and wet bed bore (right, d_0 = 0.82m, h_0 = 0.05m) on rough bed.

5 RESULTS

It was shown by Wüthrich et al. (2017) that the surges produced through the vertical release technique were similar to the classical dam-break scenario on smooth bed described by the theory of Ritter (1892). The latter assumed the sudden removal of a gate in front of an infinite reservoir under ideal fluid conditions, producing a wave propagating over a smooth horizontal surface. The longitudinal wave profiles obtained when the dry bed surge reached x = 13.85 m (location of US 7) were successfully compared to the theoretical solutions proposed by Ritter (1892) and Chanson (2009), as shown in Figure 4. Unfortunately, the smooth bed condition is merely theoretical and the influence of bed friction was implemented by Dressler (1952; 1954) and Whitham (1955). The profiles obtained for the experiments over rough bed were compared to these theoretical solutions in Figure 4, where a good match can be observed with Whitham (1955) and Chanson (2009). The results were also compared with the experimental data of Schoklitsch (1917), where some differences can be observed, most probably attributed to the difference in surface roughness.

For wet bed bores, no differences were observed between the smooth and the rough conditions in terms of wave profiles (herein not shown) and wave front celerity (Figure 6b), showing that both scenarios were well described by the theory of Stoker (1957). These findings suggested that for the tested roughness values, the initial still water depth, h_0 had a greater influence on the resulting wave than friction.

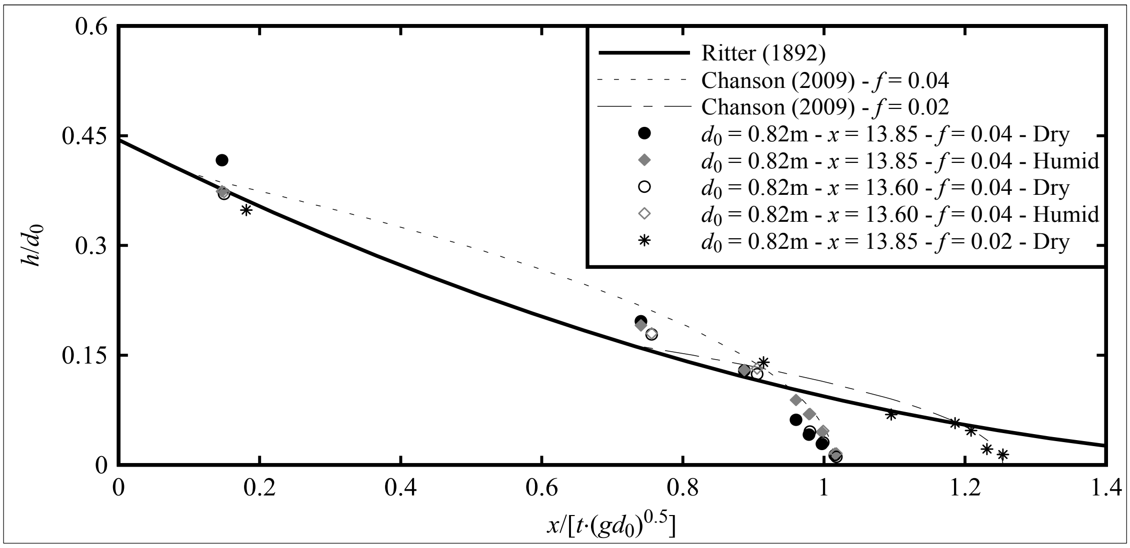

Figure 4. Comparison of longitudinal wave profiles for smooth and rough beds with theoretical solutions.

For engineers designing structures resistant to hydrodynamic loads, it is fundamental to determine the celerity U of the incoming wave. While for wet bed bores velocities can be precisely predicted using the Stoker (1957) theory, great incertitude still exists in the evaluation of front celerity for dry bed surges (Nistor et al. 2009, Wüthrich et al. 2017). For dry bed surges, it is commonly assumed in the literature that:

$$U = \alpha\sqrt{gd_0} \qquad [1]$$

where U is the wave front celerity, d_0 the equivalent impoundment depth and α is a parameter whose value is covered by high uncertainties. The velocity coefficient, α can also be expressed as a dimensionless velocity:

$$\alpha = \frac{U}{\sqrt{gd_0}} \qquad [2]$$

and various values of α can be found in literature; the most relevant ones are presented in Table 2. The same values are presented graphically in Figure 5 and compared to the experimental results of the present study.

Table 2. Coefficient α in Eq. [1] and [2].

Reference	α
Iizuka and Matsutomi (2000)	1.1
Kirkoz (1983)	$\sqrt{2}$
Ritter (1892), FEMA55 (2000)	2
Murty (1977)	1.83
Bryant (2008)	1.67
Matsutomi and Okamoto (2010)	0.66
Shafiei et al. (2016)	1.7
Wüthrich et al. (2017)	1.25

For the tests carried out in the present study on the smooth channel, the best approximation was found with a coefficient α = 1.3 (Figure 5). As previously discussed, this value slightly underestimated the waves with higher values of d_0 and overestimated the lower ones.

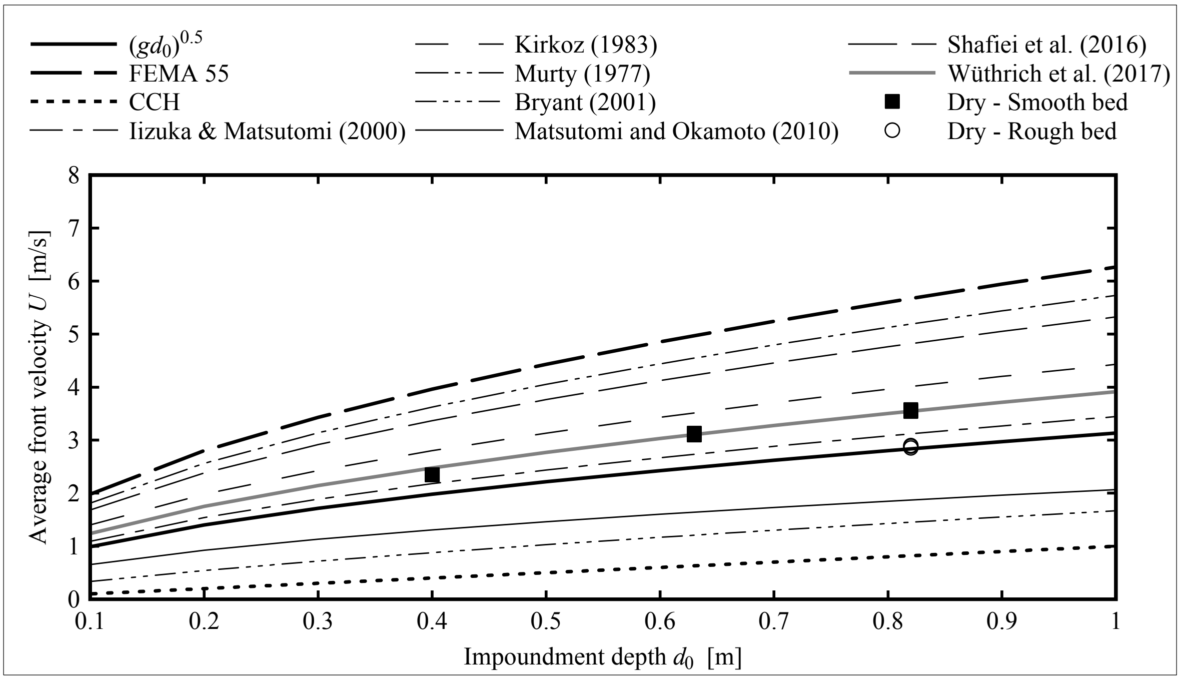

Figure 5. Comparison of experimental data with previous existing formulae.

The values presented in Table 2 and Figure 5 for the smooth configuration, were also compared to the experimental tests obtained for the rough bed. A significant influence of roughness was observed and lower celerity values were measured over rough bed, leading to an overestimation of the celerity values up to 25 % for a coefficient α = 1.3. These findings clearly indicated a dependence of α on the friction factor f that should be taken into account in the prediction of the incoming wave celerity. For wet bed bores, the roughness was shown to have a less significant influence and the same celerity values were recorded for both smooth and rough scenarios. Both behaviours are presented in Figure 6, in which the values of α were plotted as a function of the friction factor, f. The decreasing behaviour of α for larger values of f confirms its dependence on the bed roughness for dry bed surges. In this preliminary study, only two roughness values were tested, implying that only an overall indication of this relationship can be drawn; further studies are therefore necessary to implement it.

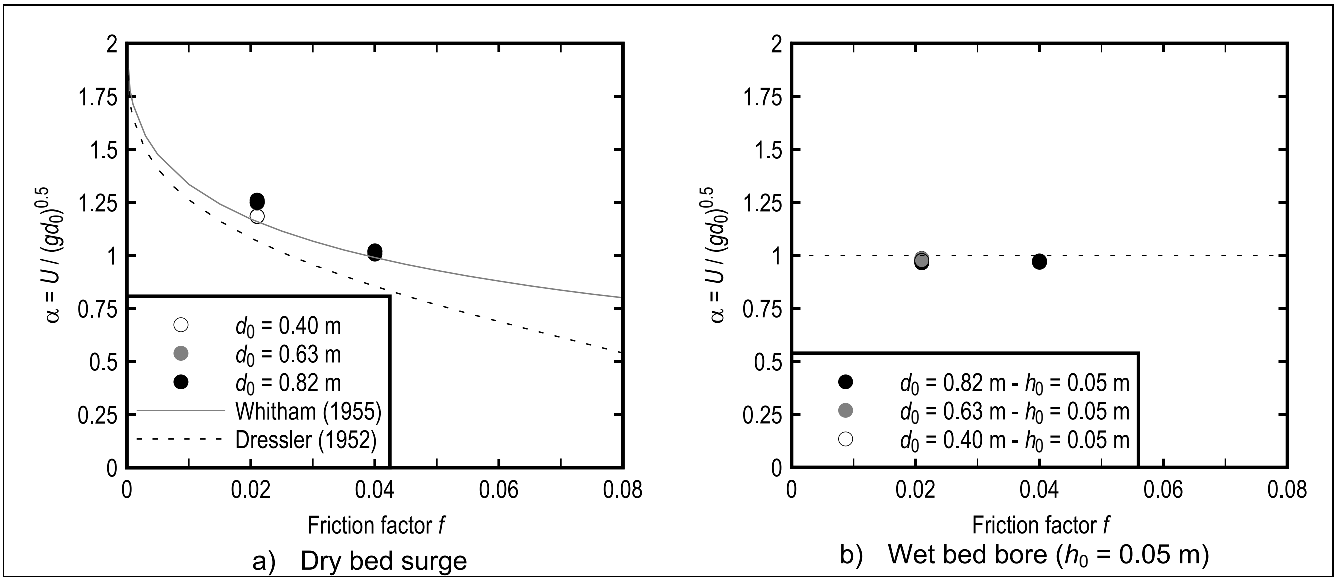

Figure 6. Velocity coefficient α as a function of friction factor f for both dry bed surges and wet bed bores.

The experimental points were also compared to some existing theories found in literature, mainly in Dressler (1952; 1954) and Whitham (1955). Dressler (1952) solved the Saint-Venant equations using a perturbation method assuming a constant friction factor, leading to the Eq. [3] (readapted by Chanson, 2004).

$$\frac{U}{\sqrt{g \cdot d_0}} = \frac{2}{3}\left(1 + \frac{x}{t \cdot \sqrt{g \cdot d_0}}\right) + F_1 \cdot \frac{f}{8}\sqrt{\frac{g}{d_0}} \cdot t \tag{3}$$

where F_1 is a first order correction factor for the flow resistance, whose value is expressed in Eq. [4].

$$F_1 = -\frac{108}{7\left(2 - \frac{x}{t \cdot \sqrt{g \cdot d_0}}\right)^2} + \frac{12}{2 - \frac{x}{t \cdot \sqrt{g \cdot d_0}}} - \frac{8}{3} + \frac{8\sqrt{3}}{189} \cdot \left(2 - \frac{x}{t \cdot \sqrt{g \cdot d_0}}\right)^{\frac{3}{2}} \tag{4}$$

An analogous solution was proposed by Whitham (1955), solving the Saint-Venant equations using an adaptation of the Polhausen Method (Chanson, 2004), leading to Eq. [5].

$$\frac{U}{\sqrt{g \cdot d_0}} = \frac{2}{1 + 2.90724\left[\left(\frac{f}{8}\right)\sqrt{\frac{gt^2}{d_0}}\right]^{0.4255}} \tag{5}$$

For both theories, on a completely smooth surface ($f = 0$), a celerity value equal to the propagation of the forward characteristic in the Ritter (1892) theory can be assumed, implying $\alpha = 2$. An asymptotic behaviour toward this value can be observed in Figure 6a for $f \to 0$ leading to a vertical tangent. For large roughness values ($f \to \infty$), zero velocity should be expected, implying $\alpha = 0$, even if this scenario is physically impossible. This represents a limitation for both theories of Whitham (1955) and Dressler (1952; 1954) that are no longer valid for large tip regions, i.e. for large roughness values (Chanson, 2004). Figure 6 shows a relative good match for low friction factors with both theories, however, differences become more important for rougher surfaces and Whitham (1955) theory represented the experimental tests better.

6 CONCLUSIONS

In the design phase of structures resistant to hydrodynamic loading, the estimation of the approaching velocity is fundamental. Previous studies and field surveys showed that the disagreement and high incertitudes still exist in the evaluation of this parameter. The present study was based on an experimental approach and it focused on the evaluation of wave front celerity. Waves were reproduced in a large scale facility through a vertical release technique and both a smooth and a rough surface were tested. Produced waves were investigated in terms of wave height using Ultrasonic Distance Sensors located along the channel, allowing the estimation of the average wave celerity. The wave profiles were shown to be in agreement with existing theories in the domain of dam-break waves for both smooth and rough horizontal beds. While no influence of bed roughness was observed for wet bed bores, results clearly showed a dependence of the wave celerity on the friction factor for dry bed surges. For the two tested roughness values, lower celerity were observed for higher roughness, suggesting that friction should be considered when estimating the approaching velocity of a tsunami inland. The experimental points showed good agreement with previous theoretical solutions found in the literature. Nevertheless, only two values were investigated, pointing out the need of a more extensive experimental work to validate these preliminary results.

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NOTATION

d_0	equivalent impoundment depth [m]
f	Darcy-Weissbach friction factor
F_1	first order correction of flow resistance in Eq. [3]
g	gravity constant [m/s^2]
h	wave height [m]
h_0	initial still water depth [m]
h_{max}	maximum wave height [m]
t	time [s]
U	wave front celerity [m/s]
x	longitudinal coordinate along the channel [m]
α	velocity coefficient, defined as $U/(gd_0)^{0.5}$
Δt	increment in time [s]
Δx	Increment in distance [m]

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